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Ecological impact of historical and future land-use patterns in Senegal

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Abstract

The CENTURY model was used to simulate changes in total system carbon resulting from land-use history (1850–2000), and impacts of climatic changes and improved land-use management practices in Senegal. Results show that 0.477 Gtons of carbon have been lost from 1850 to 2000. Improved management practices have the potential of increasing carbon levels by 0.116 Gtons from 2000 to 2100. Potential to store carbon exists for improved forest management and agriculture practices in southern Senegal. Potential climatic changes decrease plant production (30 percent), total system carbon (14 percent), and the potential to store carbon from improved management practices (31 percent).

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1. Introduction

During the past 20 years, there has been substantial interest in evaluating the impact of historical land-use patterns on natural and managed ecosystems (Ojima et al., 1993; Houghton, 1994; Ramankutty and Foley, 1999; Palm et al., 2004). Specifically, there is interest in determining how land use changes have altered the carbon budget, trace gas fluxes, nutrient cycling, and sustainability of ecosystems at local, regional and global scales (Matson et al., 1997). This interest is driven by

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concerns about the impact of anthropogenic activities on greenhouse gas fluxes, and the impact of greenhouse gas concentrations on managed and natural ecosystems, and the global climate system (IPCC, 2000, 2001). These concerns have led to scientific efforts to quantify historical land-use patterns at regional and global scales (Meyer and Turner, 1994; Lambin, 1997; Ramankutty and Foley, 1999). New historical land-use databases are now being used to drive ecosystem models (Carter et al., 1993; Parton and Rasmussen, 1994; Howard et al., 1995; Kelly et al., 1997). The historical land-use data needed to drive ecosystem models includes information about temporal changes in dominant crop rotations, tillage practices, inorganic and organic fertilizer additions, crop yields, crop harvesting practices, crop varieties, and planting and harvesting dates.

The potential impact of land use changes, climatic variability, and climatic change on ecosystems in Africa have been highlighted in a series of papers (Cao et al., 2001; Desanker and Justice, 2001; Gonzalez, 2001; Nicholson, 2001) which evaluate how land-use change could alter the climate of Africa and how both land use and recent climatic trends (decreasing precipitation in semi-arid regions of West Africa) have impacted ecosystems in Africa. Olsson and Ardö (2002) used the CENTURY model to simulate changes in soil carbon levels in Sudan and found that increasing the fallow periods and converting marginal agricultural regions to grasslands will substantially increase carbon storage. Ardö and Olsson (2003) and Liu et al. (2004) used spatially explicit databases from semi-arid Sudan and Senegal as input into the CENTURY model and then simulated regional estimates of historical changes in soil carbon and projections for the next 100 years. Woomer et al. (2004) used the CENTURY model to simulate historical changes in carbon levels for Senegal's Sahel Region, and Tschakert et al. (2004) simulated the impact of observed land use changes, improved land-use management and potential future climatic change on total carbon levels in the Old Peanut Basin of Senegal. Stéphane and Lambin (2001) recently developed a land-use change model for Sudano-Sahelian African countries that simulates land-use change as a function of human population, livestock and rainfall. This model has the potential to be linked to plant–soil ecosystem models like the CENTURY model.

Increased attention on the role land management can play in offsetting carbon emissions and other greenhouse gases has received substantial attention due to the inclusion of carbon sequestration considerations in the Kyoto Protocol (Noble and Scholes, 2001). The initial focus deals with afforestation and reforestation land management practices. However, international negotiations continue regarding the carbon sequestration in soils. Various strategies which allow for land-use related carbon sequestration as a component of conservation activities are being considered (Noble and Scholes, 2001; Lal, 2002). In semi-arid ecosystems, soil carbon represents the vast store of carbon in the system (Ojima et al., 1993; Follett et al., 2001) and may be a potential sink for carbon sequestration under improved management schemes. Model estimates of recovery of over-grazed lands in semi-arid regions show a substantial potential to store soil carbon and to improve rangeland conditions (Ojima et al., 1993). The implementation of Clean Development Mechanisms within the Kyoto Protocol provides for consideration of soil carbon sequestration.

The primary goal of this paper is to quantify the historical (1850–2000) changes in system-level carbon for Senegal and to project changes resulting from climate change scenarios and the implementation of the best management practices during the next 100 years. Senegal is a country in the Sahelian and Sudanian Regions of West Africa where the rainfall ranges from 300 mm yr⁻¹ in northern Senegal to over 1000 mm yr⁻¹ in southern Senegal. The natural vegetation includes savanna grasslands in the north and woodlands in the south. The reconstructed land-use history for the major ecoregions in Senegal are linked to the CENTURY ecosystem model (Parton et al., 1993) to simulate changes in system-level carbon for each of the ecoregions, and then used to project potential carbon sequestration resulting from improved land-use management practices. The important Senegal land-use systems include dryland agriculture, grazing, irrigated agriculture along the Senegal River, and charcoal production from woodlands. In the northern third of Senegal, grazing is the dominant land use. Dryland agriculture is important in the Peanut Basin (east-central part of Senegal), while charcoal production and dryland agriculture are significant land uses in the southern woodland regions of Senegal (Pélissier, 1966; Stancioff et al., 1986).

Senegal has experienced substantial population increases during the last 100 years. This led to increases in intensity and area of cultivated agriculture, increased grazing intensity by cattle and goats (consumption of both trees and grass), expansion of grazing area due to drilling of water wells in northern Senegal, and recent (since 1970) increases in the removal of trees for charcoal production. All of these activities have greatly reduced the system level carbon in Senegal. Projected improved managements include reduction in cattle grazing levels and lopping of trees for animal consumption, increases in the grass fallow period and the addition of manure (collected from cattle pens and grasslands), and reduction in wood removal for charcoal production. These scenarios are optimistic potential land-use practices and would likely be difficult to implement because of economic and social constraints in Senegal.

2. Century model description

CENTURY is a generalized ecosystem model that simulates the dynamics of carbon, nitrogen, and phosphorus in grassland, forest, savanna, and crop systems (Metherell et al., 1993; Parton et al., 1993). The model includes plant production, nutrient cycling, water flow, and soil organic matter submodels (Fig. 1). The plant production and water flow models use monthly time steps, while the nutrient cycling and soil organic matter submodels use weekly time steps. Observed monthly precipitation and average monthly daily maximum and minimum temperatures are the major abiotic driving variables. Soil texture, bulk density, soil depth, soil field capacity, and wilting point are the important soil input variables. The cropping system and grassland components of CENTURY have been tested extensively, showing that the model can correctly simulate the impact of different cultivation practices (Metherell et al., 1995), cropping systems (Kelly et al., 1997), and organic and inorganic fertilizer application (Paustian et al., 1992; Parton et al., 1993; Parton and Rasmussen, 1994) on observed changes in soil C and N levels, soil nitrogen mineralization, and grass and crop yields.

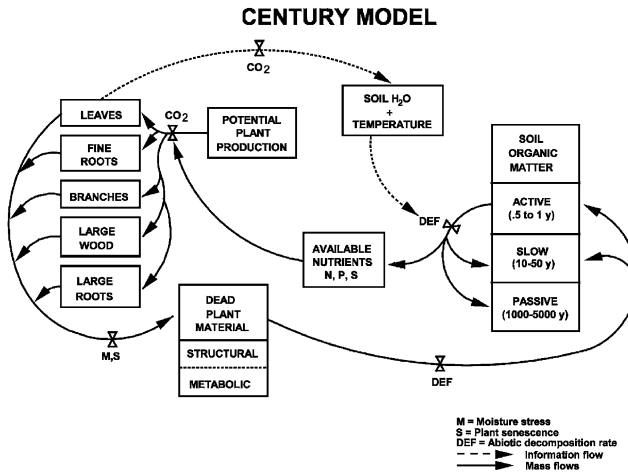


Fig. 1. CENTURY model flow diagram showing the major components and flows for the plant-soil ecosystem model.

The CENTURY model (Fig. 1) calculates potential plant production and nutrient uptake as a function of soil water stress, leaf area index, and soil temperature, and then limits plant production based on soil nutrient availability. Soil nutrients are mineralized as a result of decomposition of dead plant material and soil organic matter pools. The soil organic matter submodel includes dead plant material and three soil organic matter pools (active, slow, and passive). A complete description of the structure of the CENTURY Model and the equations used to describe carbon and nutrient flows are presented by Parton et al. (1988, 1993).

The CENTURY model simulates the impact of land-use change on ecosystem dynamics by using schedule files that define the land use and management practices for each month of the year during the computer run. The model has a software package (Metherell et al., 1993) that allows the model user to define timing of different land-use management practices and includes a library of crop tillage practices, inorganic and organic fertilizer amounts, harvest practices, tree removal practices, tree and grass burning practices, and different crops, trees, and grasses. The model has been parameterized for the major crops, grasses, and trees grown in the world, and can be easily adjusted to represent site-specific crops, grasses, or tree varieties.

3. Senegal land-use data

Land-use history data was constructed for the major ecoregions in Senegal using a variety of data sources. Ecoregions are generally considered to be regions of relative homogeneity in ecological systems involving inter-relationships between organisms and their environment (Omernik, 1987). In this paper, we present a description of the land-use data while papers by Tappan et al. (2004) and Wood et al. (2004) give more

information about historical land use and land cover trends for Senegal. Fig. 2 shows the location of Senegal's ecoregions. CENTURY model runs were not set up for the Senegal River Valley and Estuary Regions because of difficulty representing flooding and inputs of nutrients from the river systems. The Dakar Region, with its predominantly urban character, and the narrow coastal Niaye Region, with its wetlands and sand dunes, were also excluded from our analysis. Appendix A presents a summary of the historical land-use patterns from 1850–2000 for each of Senegal's major ecoregions and the projected changes in land-use practices for the next 100 years. The CENTURY schedule files that represent these land-use patterns are available on the CENTURY web site (<http://www.nrel.colostate.edu/projects/century/>).

The northern part of Senegal is a pastoral region with a natural savanna ecosystem (Fig. 2) that includes the Northern Sandy Pastoral Region, the Ferruginous Pastoral Region, and the Southern Sandy Pastoral Region (Stancioff et al., 1986; Tappan et al., 2004). Model results from these regions will be aggregated and referred to as the Pastoral Region. These regions have similar land-use histories and are primarily grazed by cattle, sheep, and goats with minimal cultivated agriculture. Prior to 1950, the Pastoral Region was lightly grazed during the summer months, but during the 1950s there was a major expansion of water wells in the region that allowed for a dramatic increase in animal grazing and human population (Michel et al., 1969; Valenza and Diallo, 1972). This change resulted in increased grazing levels and lopping of trees for consumption by animals during winter dry season. The Ferruginous Pastoral Region has lower plant production because of shallow rocky soil with low soil water holding capacity (Stancioff et al., 1986). The grazing rates on the laterite soils are assumed to be lower because of lower plant production on these sites. The projected future change to the land use in the Pastoral Region is to reduce the 1990s grazing and tree lopping rates by 50 percent from 2000 to 2100.

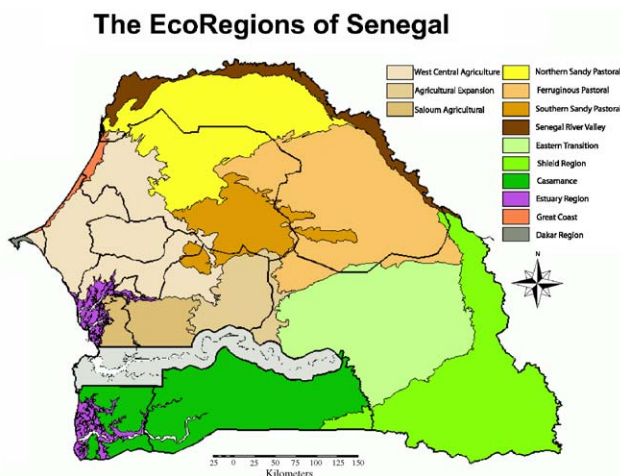


Fig. 2. Location of the major ecoregions in Senegal. Each region has similar climatic and land-use practices.

Senegal's dominant agricultural regions are in the western and central parts of the country and include the West-Central Agriculture Region, the Agricultural Expansion Region, the Saloum Agricultural Region, and intensive agricultural land within the Casamance. Model results for these regions will be aggregated and referred to as the Intensive Agriculture Region. Portions of these regions have had substantial dryland agriculture areas since the early 1900s (West-Central Agriculture Region and Saloum Agricultural Region), and have generally been referred to as the Peanut Basin (Pélissier, 1966). The Peanut Basin agriculture uses a dryland agriculture millet–groundnut–sorghum–fallow rotation with different periods of fallow (0–20 years of grass fallow separating the growing of crops) during the last 100 years. Currently land pressure is so great that fallow periods are minimal. However, 10–20 year grass fallow was common in the early 1900s. A detailed description of this crop rotation is presented by Tschakert et al. (2004). The Agricultural Expansion and Casamance Regions use similar crop rotations with significant crop expansion starting in 1940. The projected land-use change from 2000 to 2100 for the Intensive Agriculture Region is to double the length of the grass fallow period (from 5 to 10 years) and to add more farmyard manure ($87 \text{ tons mg C ha}^{-1} \text{ yr}^{-1}$ with each crop).

The southern part of Senegal is dominated by natural woodlands with relatively high plant production and woody biomass (Lawesson, 1995). This area includes the Eastern Transition Region, the Shield Region, and the Casamance Region. These regions had relatively minor anthropogenic impacts prior to 1960, with light grazing levels, minimal forest clearing, and a small area in cultivated agriculture. After 1960, there was a substantial increase in grazing pressure and forest clearing for charcoal production in the Eastern Transition Region (Tappan et al., 2004). The Shield Region has had minimal impact of man except for increased grazing and grass fire frequency after 1970. The Casamance Region was grazed lightly prior to 1960 (Pélissier, 1966). After 1960, there was an increase in cattle grazing and grass fire frequency, and an increase in the amount of land that was cultivated, while forest clearing for charcoal production increased dramatically after 1990 (Bienvienu Sambou, University of Dakar, pers. comm.). To obtain annual fire frequency estimates, we visually interpreted dry season Landsat images of southern Senegal spanning 30 years. The projected future land-use modifications are to reduce forest clearing for charcoal production to 50 percent of the 1990 levels and to double the fallow period for the cultivated agricultural regions. We assumed no changes in the current land-use patterns for the Shield Region because of the low population density. Model results will be aggregated for the Eastern Transition and non-agriculture parts of the Casamance Regions and referred to as the Forest Transition Region.

4. Regional model runs

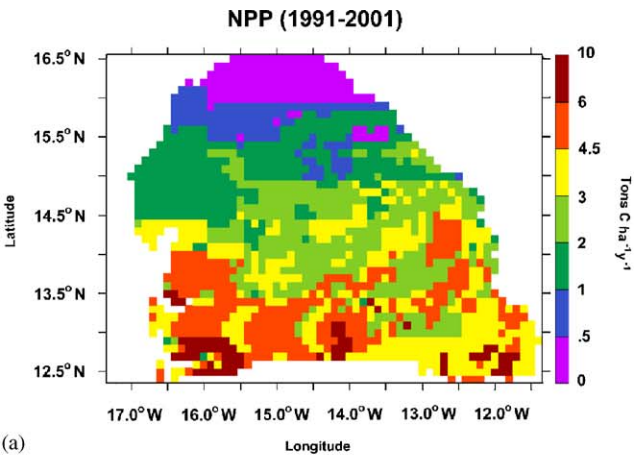
The CENTURY model was set up to simulate regional carbon dynamics for Senegal using a $10 \times 10 \text{ km}^2$ grid. Separate model runs were run for each grid point (1700 grid points) in Senegal. The driving variable data sets included: (1) observed

weather during the last 100 years, (2) the dominant soil sand, silt and clay content for each grid point, and (3) the observed land-use history for each of the Senegal ecoregions (see Appendix A). The 100-year weather data was primarily derived from the Jones et al. (1999) global 0.5×0.5 degrees weather data (CRU). The observed maximum and minimum air temperature data all came from the CRU data set, while the monthly precipitation data included $10 \times 10 \text{ km}^2$ gridded precipitation data from 1961 to 1996 and the CRU precipitation data prior to 1961. The 0.5×0.5 degrees CRU weather data was interpolated to the $10 \times 10 \text{ km}^2$ Senegal grid. Each site within a particular ecoregion used the same land-use history and projections of future land use. There are a substantial number of sites with very rocky soils (laterite soils) that have low soil water holding capacity and ability to stabilize soil organic matter. We represent laterite soils by assuming very low soil water holding capacity, soil depth (30 cm depth), and high surface water runoff rates. We also assumed that laterite soils had 50 percent of the nitrogen inputs compared to other sites. These assumptions generated lower plant production and soil carbon levels for the laterite soils compared to non-laterite soils.

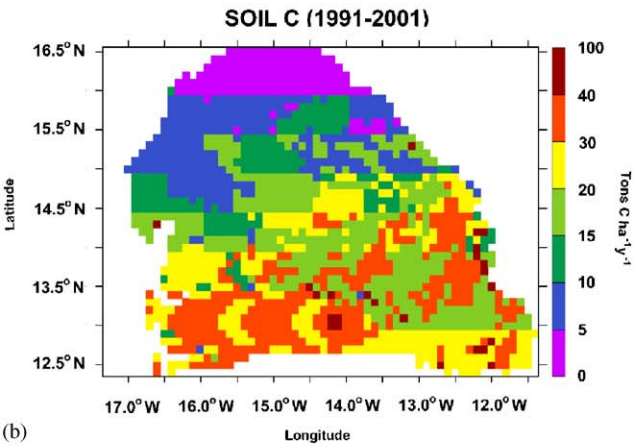
Model runs were set up to simulate the potential impact of climatic change on ecosystem carbon levels and the ability to store carbon in Senegal ecosystems using improved management practices. We assumed that the precipitation would linearly decrease by 20 percent and air temperatures would linearly increase by 2EC (both maximum and minimum air temperature) to simulate climate change between 2000 and the year 2100 model years. Model simulations were run for the conventional management practices (continuation of present practices) and the improved management practices from 2000 to 2100 using the above climate change scenario. This scenario was used in order to be consistent with the climate change scenarios used by Liu et al. (2004) and Tschakert et al. (2004). These climate change model runs are compared to the standard model runs where we used the observed climate data from 1960 to 2000 as the input weather data for the 2000–2100 year simulations for standard and improved land-use management practices.

5. Century model results

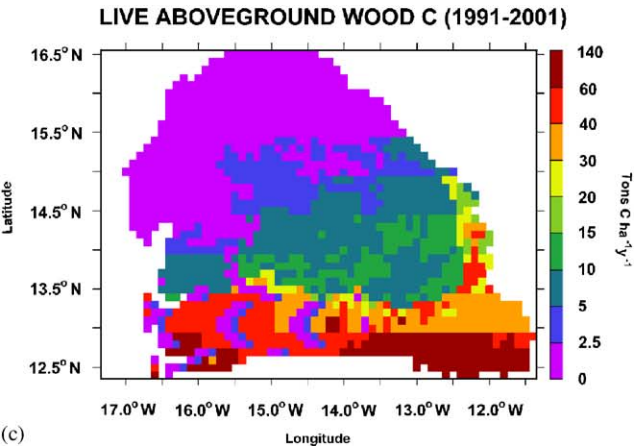
Observed plant production, soil carbon and wood carbon data are available to test the simulated patterns for these variables in Senegal. Above-ground tree leaf and grass production data (Sala, *Centre de Suivi Ecologique* (CSE), pers. comm.) for Senegal show that combined above-ground tree leaf and grass production is greater than $1.7 \text{ tons C ha}^{-1} \text{ yr}^{-1}$ in southern Senegal and decreases to less than $0.40 \text{ tons C ha}^{-1} \text{ yr}^{-1}$ in northern Senegal. The decreasing plant production follows the general trend of decreasing annual precipitation going north within Senegal. Preliminary remote sensing estimates of plant production in Senegal (Tiessen, USGS, pers. comm.) show the same pattern of decreasing plant production going northward in Senegal. The spatial simulated model results from 1990 to 2000 (Fig. 3a) show a pattern of decreasing total plant production (7.0 to $<1.0 \text{ tons C ha}^{-1} \text{ yr}^{-1}$ from south to north in Senegal) and above-ground leaf (tree



(a)



(b)



(c)

plus grass—not shown in the figure) production (1.7 to <0.40 tons C ha⁻¹ yr⁻¹ from south to north in Senegal) going northward in Senegal. The observed wood and soil carbon data from several studies (Liu et al., 2004; Tschakert et al., 2004; Woomer et al., 2004) suggest a general trend of decreasing wood carbon (> 60 tons ha⁻¹ in the south vs. < 5 tons ha⁻¹ in northern Senegal) and soil carbon (> 30 tons ha⁻¹ in the south vs. < 10 tons ha⁻¹ in northern Senegal) going northward in Senegal with model results showing the same trend. Tschakert et al. (2004) also compared CENTURY model results from the Old Peanut Basin region with observed crop yield and soil carbon data for Bambey. It is difficult to perform an exact comparison of the observed plant production, and soil and wood carbon with model results since soil texture, climate and land-use history are not available for these sites (required variables needed to run the model).

Model results show the changes in plant carbon, soil carbon, and total system carbon (Fig. 4) for the Pastoral Region, Forest Transition Region, Shield Region and the Intensive Agriculture Region. The Pastoral Region had stable carbon levels prior to 1950 when increased grazing and tree lopping caused plant carbon to be decreased by 50 percent at the end of the century. Most of the total system carbon loss comes from a reduction in plant carbon and a minimal decrease in soil carbon. The Forest Transition Region has a large drop in plant carbon from 1980 to 2000 as a result of tree removal for charcoal production and small changes in soil carbon. The Shield Region results show a slight decrease in total system carbon (approximately 8 tons ha⁻¹) from 1975 to 2000 with most of the loss coming from a decrease in plant carbon levels. From 1900 to 2000, the Intensive Agricultural Region experienced large losses of plant and soil carbon (total loss > 50 tons ha⁻¹) associated with intensive agricultural practices. An analysis of the carbon budget for the whole country of Senegal shows that 0.477 Gtons carbon have been released to the atmosphere since 1875 due to land-use change with over 80 percent of the release coming since 1950 primarily from a decrease in the plant carbon pool (mostly woody biomass). The vast majority of the carbon losses (> 90 percent) came from the Intensive Agricultural Region and the Forest Transition regions. Note that the simulated maps of soil C and live wood C for 2000 (Figs. 3b and c) include the large losses of C due to historical land-use practices.

Simulated comparison of conventional management vs. the improved management practices for 2020–2090 (Fig. 5) show a slight increase in plant and soil carbon (equal amounts from plant and soil carbon) with improved management for the Pastoral Region (1.5 tons ha⁻¹ total). Improved management of the Forest Transition Region from 2020 to 2090 show a substantial increase (8.2 tons ha⁻¹) in total system carbon with > 90 percent of the increase coming from increasing plant carbon. There were no changes in system carbon for the Shield Region because management was not changed. Improved management resulted in the largest increases (17.1 tons ha⁻¹) in total system carbon for the Intensive Agriculture Region



Fig. 3. Simulated regional maps of (a) average annual (1990–2000) net plant production, (b) average soil carbon levels (1990–2000), (c) average above-ground live wood carbon (1990–2000) using the CENTURY model.

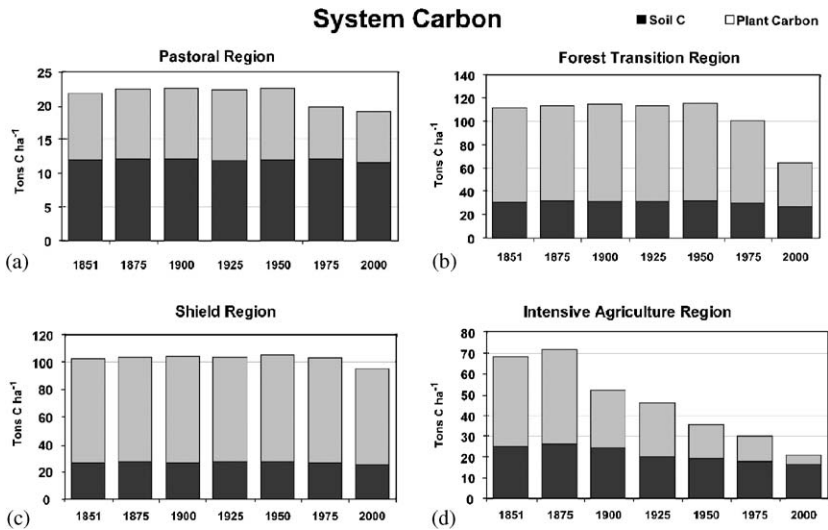


Fig. 4. CENTURY model simulated total system carbon, plant carbon and soil carbon for the (a) pastoral, (b) forest transition, (c) shield regions and (d) intensive agriculture in Senegal from 1850 to 2000.

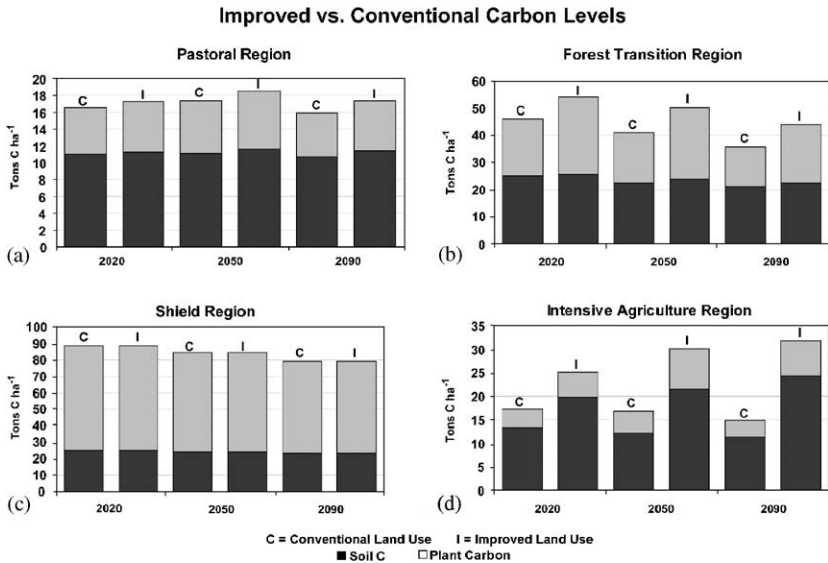


Fig. 5. Simulated total system carbon, plant carbon, and soil carbon for the (a) pastoral, (b) forest transition, (c) shield regions and (d) intensive agriculture in Senegal from 2020 to 2090 for the improved management and control simulations (1960–2000 weather used).

with most of the increase (90 percent) coming from increased soil carbon levels. These results are not surprising since the grass fallow period was lengthened to 10 years and both manure and household waste were added to the cropped fields. This

is a very optimistic scenario but gives an index about how much carbon could be stored in the Intensive Agricultural Region. Comparison of carbon stored from improved management after 20 years vs. 90 years shows that approximately half of the total carbon storage in 100 years occurs in the first 20 years for the Pastoral and Intensive Agriculture Regions, while >95 percent of the management influence on carbon stocks occurs in the first 20 years for the Forest Transition Region. Analysis of the carbon budget at the national level shows the 0.074 Gtons of carbon would be stored after 20 years of improved management and 0.043 Gtons would be stored from 2020 to 2100. Maps of potential carbon gains in Senegal (Fig. 6) from improved management after 20 years and 100 years show the largest gains are in the Intensive Agriculture and Forest Transition Regions. Results for the Intensive Agriculture and

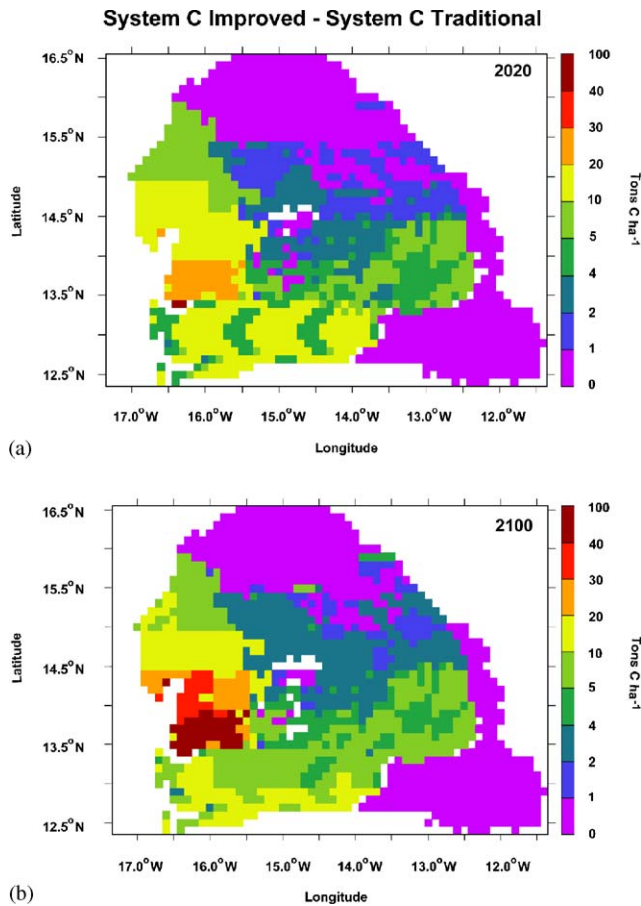


Fig. 6. CENTURY model simulated patterns of changes in total system carbon resulting from improved management (improved management minus control run) during (a) the 2000–2020 time period and (b) the 2000–2100 time period (1960–2000 weather used).

Forest Transition Regions show a general trend for increasing carbon storage potential going southward within Senegal, suggesting that carbon storage potential is positively correlated to rainfall and plant production (precipitation increases going southward in Senegal). It is important to note that there is a general trend for decreasing total system carbon for both the improved and control computer runs from 2000 to 2100 for all of the regions except the Intensive Agriculture Region where total system carbon increased for the improved runs. The continued decrease in system carbon from 2000 to 2100 results from using 1960–2000 weather for the 2000–2100 time period (precipitation was 20 percent lower for 1960–2000 compared to the long term mean precipitation) and residual impacts of continuing current management practices.

Climatic change runs from 2000 to 2100 (Fig. 7) show that decreasing precipitation and increasing temperature cause decreases in total system carbon (42 and 31 percent, respectively, for the conventional and improved land use after 100 years) and the amount of carbon stored with improved management practices (21 and 36 percent, respectively, for years 2020 and 2100 compared to the extended current climate runs). Both the extended current climate runs (1960–2000 weather) and the climate change runs show that most of the carbon gains from improved management have occurred before year 2030. Climate change and extended current climate runs both show that virtually all of the carbon gains from improved management in the Forest Transition Region occur by 2025, while the substantial carbon gains continue for 100 years in the Intensive Agriculture Region (data not shown). The simulated pattern of reduced increases in system carbon for improved land-use management with climate change is probably a result of the 30 percent decrease in plant production for the climate change runs compared to current climate runs. These results are consistent with regional patterns for carbon storage with improved management (Fig. 6) showing decreasing carbon storage with lower precipitation and plant production going northward in Senegal and suggest that the potential to store carbon using improved management is positively correlated to annual precipitation and plant production.

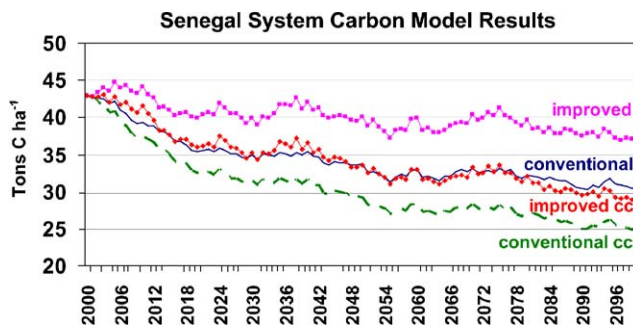


Fig. 7. Simulated changes in Senegal total system carbon for conventional and improved land-use management for 2000–2100 using climatic change (cc, reduced precipitation and increased air temperature) and for a controlled climate case (extending the 1960–2000 climatic patterns).

6. Discussion

The roles of residue management and fallow in the semi-arid ecosystems in Senegal are crucial to the long-term sustainability of soil fertility and yield from different agroecosystems (Manley et al., 2002c). In a study in southern Senegal, organic matter management in cropping systems was found to be critical in the development of mitigation strategies (Manley et al., 2002c). The simulated response to alteration in fallow and organic matter addition practices of the groundnut systems are consistent with the findings of Manley et al. (2002a). CENTURY model simulated improved fallow periods and residue management showed enhanced soil fertility and soil organic matter storage for these cropping rotations. Model results for historical land-use practices show that 50.5 tons ha⁻¹ (0.206 Gtons carbon) were released to the atmosphere due to agricultural development in the Intensive Agriculture Region from 1875 to 2000, with substantial carbon loss from both the plant and soil carbon pools. Model runs assuming improved management show that increasing the fallow period to 10 years and adding household and farmyard manure increased system carbon levels in the Intensive Agriculture Region by 7.8 tons ha⁻¹ after 20 years (0.031 Gtons carbon) and 17.1 ton/ha after 100 years (0.068 Gtons carbon). Over 90 percent of the increase in the soil carbon pool and approximately 50 percent of the Senegal national potential to store carbon comes in the Intensive Agriculture Region. These assumed management practices are quite optimistic given the current population growth in Senegal and practicality of finding sufficient organic matter inputs for the agricultural fields and thus give an upper bound for potential increases in system levels of carbon for the Intensive Agriculture Region.

The savanna simulations from CENTURY indicated that woody biomass accumulation can be a carbon sink and annual accumulation can be positive even under low precipitation. However, forest use can have an adverse effect on the store of carbon. Fuel wood collection, changes in fire suppression efforts, and slash-mulching practices can alter the amount of above-ground biomass maintained in the system. Model results suggest that removal of above-ground tree biomass for charcoal production from 1950 to 2000 has resulted in a decrease in ecosystem level carbon of 51.6 tons ha⁻¹ (0.223 Gtons carbon) for the Forest Transition Region with 90 percent of the carbon loss coming from a decrease in plant carbon levels. Implementation of improved management of the forest (50 percent reduction in forest clearing for charcoal production) results in an increase in system level carbon of 8.0 tons ha⁻¹ (0.035 Gtons carbon) after 20 years compared to current land-use practices. Development of the mitigation strategies dealing with alterations of current land-use practices need to work closely with local land managers. Considerations should consider stump conservation, slash-and-mulch clearing, fire suppression, and improved fallows. Improving soil fertility and carbon sequestration in Senegal is challenged by the lack of incentives to maintain these soil conservation practices (Manley et al., 2002b).

In the grazing systems, livestock and soil fertility interactions need to be considered along with localized land-use decision-making (Manley et al., 2002c). Soil

carbon in these systems can be viewed as less vulnerable to losses when maintained under consistently good management practices. This is in contrast to above-ground biomass carbon which is vulnerable to natural perturbations, such as fire or pest outbreak which can inadvertently release the stored carbon back to the atmosphere. Model results show that 3.4 tons ha^{-1} (0.019 Gtons carbon) of carbon were lost due to enhanced grazing pressure since the 1950s in the Pastoral Region with >95 percent of the loss coming from the plant carbon pool. The simulated impact of a 50 percent reduction in grazing and tree lopping rates in the Pastoral Region increases system level carbon by 0.8 tons ha^{-1} (0.004 Gtons) and 1.5 tons ha^{-1} (0.008 Gtons) respectively, after 20 and 100 years compared to current land-use management. Part of the reason for these low carbon storage rates is that soil and wood carbon levels are quite low in this region and that the 50 years of higher grazing from 1950 to 2000 did not dramatically reduce soil carbon levels. More substantial increases in system level carbon levels would result from restoration of severely degraded grazing land (e.g. land near water holes).

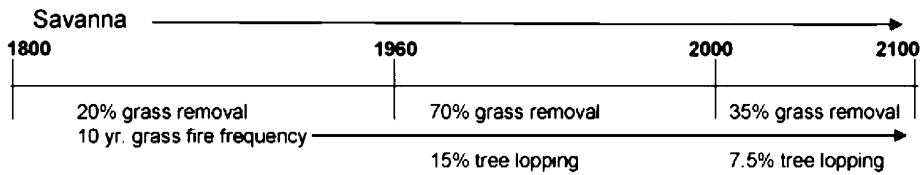
One estimate of carbon emissions from Senegal attributes nearly 40 percent to agricultural practices, land-use change and forest systems (Sokona, 1995). Our simulated results showing large losses of carbon due to current land-use practices (0.343 Gtons lost since 1950) are consistent with the results from the Sokona (1995) and suggest that carbon loss from soil C and above-ground wood C are the most important sources for the lost carbon. Model results suggest that increasing the fallow period, increasing organic inputs to the soil and reducing wood removed for charcoal have the potential to increase total system carbon by 0.073 Gtons during the next 20 years relative to the current management and 0.043 Gtons more if the practices are continued until 2100. The Intensive Agriculture and Forest Transition Regions have the greatest potential to store carbon with greater than 60 percent of the carbon gains from 2000 to 2100 realized in the first 20 years. Southern Senegal and parts of the Intensive Agriculture and Forest Transition Regions have a higher potential to store carbon since carbon storage with enhanced management is positively correlated to precipitation and plant production. This suggests that carbon sequestration demonstration projects have the greatest potential to be successful in forest restoration and agricultural improvement projects in southern Senegal.

Recent climatic trends for regions in sub-Saharan West Africa have shown 10–30 percent decreases in precipitation since 1960 (Nicholson, 2001), and the potential for further decreases in precipitation and increased air temperatures (Hulme et al., 2001) has raised concerns about the ecological impact of potential climatic change. Liu et al. (2004) and Tschakert et al. (2004) have used models to show that decreasing precipitation and increasing air temperature are expected to cause decreases in plant carbon, soil carbon, system carbon, and plant production. CENTURY model climate change runs (decreased precipitation and increased air temperature) resulted in substantial decreases in total system carbon, plant production and carbon storage with improved management in the 2000–2100 year simulations. These results confirm the previous modeling results and suggest that extrapolating current climate trends (increasing air temperature and decreasing precipitation) into the future will result in

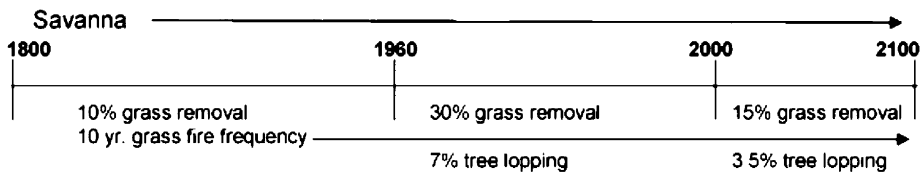
enhanced carbon loss and reduction in our ability to store carbon with improved management.

Appendix 1. Land use history from 1860 to 2000 for major bioregions in Senegal plus projections into the future

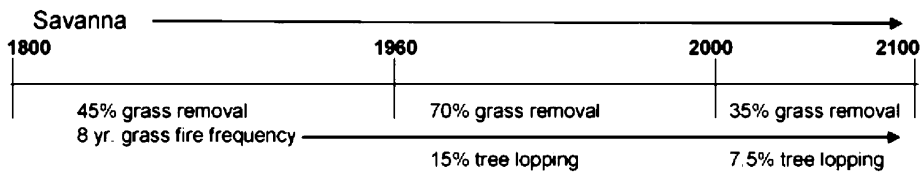
Northern Sandy Pasture (Annual Grass)



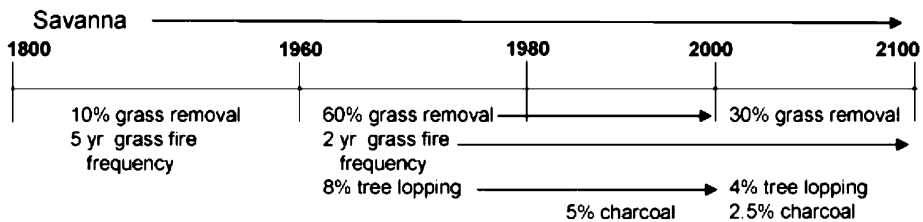
Northern Laterite Pasture (Annual Grass)



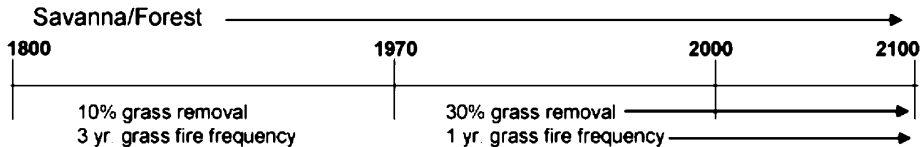
Southern Sand Pasture (Annual Grass)

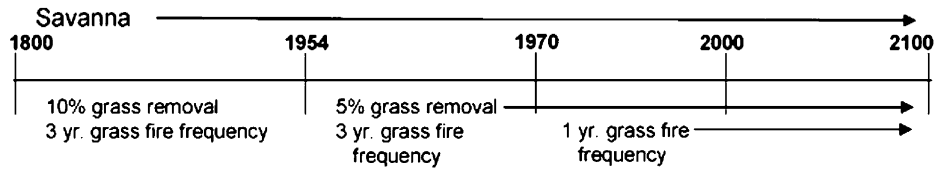
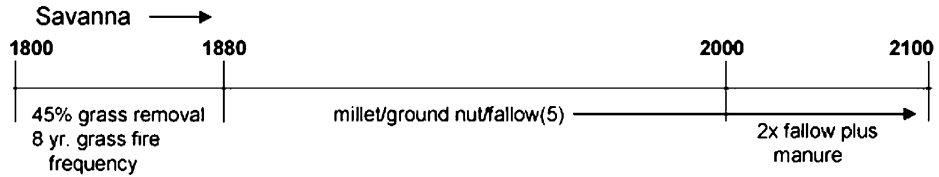
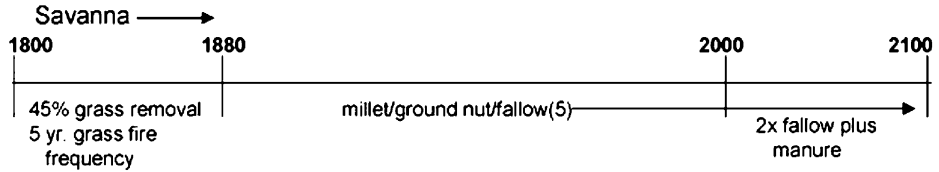
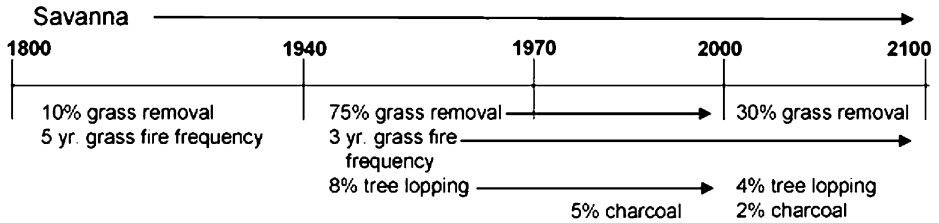
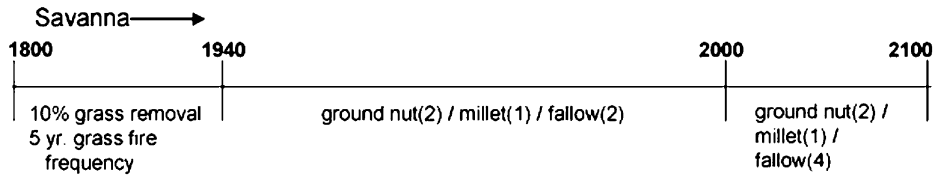


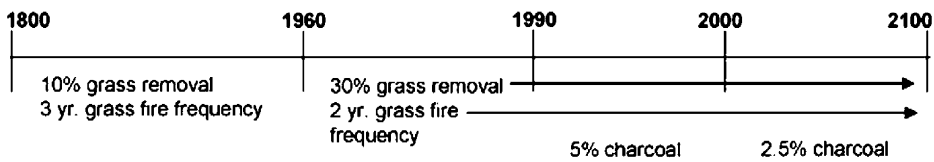
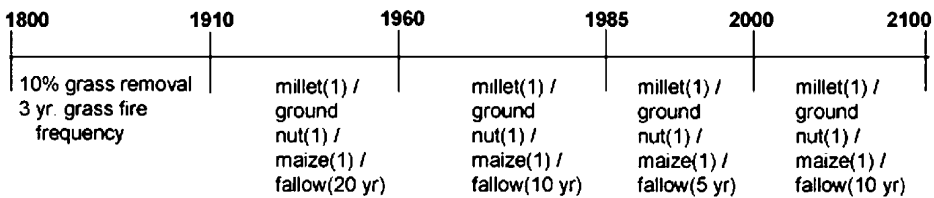
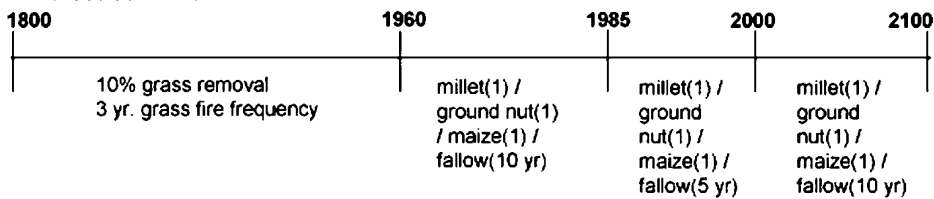
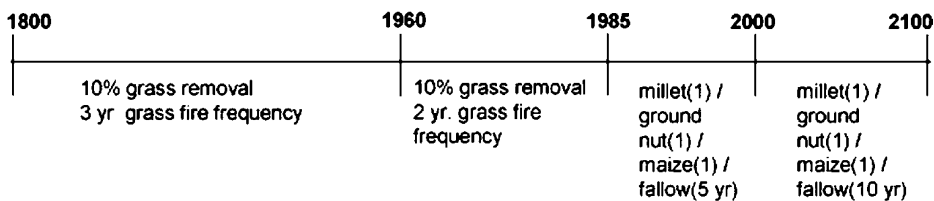
Savanna/Forest Transition (Perennial Grass)



Southeast Forest (Perennial Grass)



Southeast Park Forest (Perennial Grass)**Peanut Basin Agriculture (Annual Grass)****Southern Agriculture (Perennial Grass)****Laterite Agriculture Expansion (Perennial Grass)****Loam Agriculture Expansion (Perennial Grass)**

Southwest Forest**Forest/Savanna****Southwest Forest Large Agriculture****Forest/Savanna****Southwest Forest Intermediate Agriculture****Forest/Savanna****Southwest Forest Low Agriculture****Forest/Savanna****References**

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